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Uncertainty analysis of facemasks in mitigating SARS-CoV-2 transmission☆

Fan Liu [a,b], Hua Qian [a,c,*]

[a] School of Energy and Environment, Southeast University, Nanjing, China
[b] School of Environment and Architecture, University of Shanghai for Science and Technology, Shanghai, China
[c] Engineering Research Center for Building Energy Environments & Equipments, Ministry of Education, China

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ABSTRACT

In the context of global spread of coronavirus disease 2019 (COVID-19) caused by a novel coronavirus (SARS-CoV-2), there is a controversial issue on whether the use of facemasks is promising to control or mitigate the COVID-19 transmission. This study modeled the SARS-CoV-2 transmission process and analyzed the ability of surgical mask and N95 in reducing the infection risk with Sobol's analysis. Two documented outbreaks of COVID-19 with no involvers wearing face masks were reviewed in a restaurant in Guangzhou (China) and a choir rehearsal in Mount Vernon (USA), suggesting that the proposed model can be well validated when airborne transmission is assumed to dominate the virus transmission indoors. Subsequently, the uncertainty analysis of the protection efficiency of N95 and surgical mask were conducted with Monte Carlo simulations, with three main findings: (1) the uncertainty in infection risk is primarily apportioned by respiratory activities, virus dynamics, environment factors and individual exposures; (2) wearing masks can effectively reduce the SARS-CoV-2 infection risk to an acceptable level ($< 10^{-3}$) by at least two orders of magnitude; (3) faceseal leakage can reduce protection efficiency by approximately 4% when the infector is speaking or coughing, and by approximately 28% when the infector is sneezing. This work indicates the effectiveness of non-pharmaceutical interventions during the pandemic, and implies the importance of the synergistic studies of medicine, environment, social policies and strategies, etc., on reducing hazards and risks of the pandemic.

1. Introduction

In late December 2019, an outbreak of coronavirus disease 2019 (COVID-19) induced by a coronavirus strain (SARS- CoV-2) was reported in the Chinese city of Wuhan (Zumla and Niederman, 2020). At the time when this manuscript was written, the virus has spread worldwide with over 400 million infected people and more than 5 million deaths (D-19 Dashboard by the, 2994). Some characteristics of people are found to be associated with COVID-19 mortality, such as age over 60 years or with underlying health conditions, nonwhite race/ethnicity, income below the median and less than a high school level of education (Verity et al., 2020; de Vlas and Coffeng, 2021). Many scholars suggested that the worldwide pandemic of COVID-19 is a result of many other factors including individual immunity, mutations of the novel coronavirus, environmental factors, socioeconomic and technological aspects of countries (Coccia, 2021a; Ardito et al., 2021; Coccia, 2021b). For example, air pollution, wind speed and wind energy production have been evidenced to be linked with the number of COVID-19 cases and total deaths in the recent studies (Coccia, 2020; Coccia, 2021c; Coccia, 2021d; Travaglio et al., 2021). The development of different types of vaccines and implementations of social strategies on non-pharmaceutical interventions, such lock-down, travel restriction, social distancing, wearing facemasks also greatly contribute to reducing the hazards and risks of the COVID-19 pandemic (Abbasi, 2020; Coccia, 2022; Chu et al., 2020; Chinazzi et al., 2020; Coccia, 2021e; Wang et al., 2020; Rab et al., 2020).

However, as one of the non-pharmaceutical measures of mitigating the spread of SARS- CoV-2, mandating public or community use of face masks or covers in are hotly contested. Firstly, a substantial volume of different-type masks has been disposed as the COVID-19 pandemic progresses, which currently signifies a major source of environmental pollution (Ali et al., 2022; Shirvanimoghaddam et al., 2022). Secondly and more importantly, how well the face masks work to cut down the transmission of respiratory diseases to mask wearers is still being defined and debated (Peeples, 2020). Virus-laden particles of various sizes are emitted by infector's respiratory activities and then interact

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* Corresponding author. School of Energy and Environment, Southeast University, 2 Sipailou, Nanjing, 210096, China.
E-mail address: qianh@seu.edu.cn (H. Qian).

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with a filter fiber, by which these particles are "collected" or blocked and retained in different degrees (Kulkarni et al., 2011). Therefore, numerous studies used filtration efficiency (*FE*), i.e., the percent of the collected particles, as a metric to define the efficiency of various types of masks (van der Sande et al., 2008; Rengasamy et al., 2010; Booth et al., 2013; Milton et al., 2013; Ueki et al., 2020; Borgelink et al., 2022; Balazy et al., 2006; Grinshpun et al., 2009; Ramirez and O'Shaughnessy, 2017; Asadi et al., 2020), as some *FE* values reviewed in Table S1. However, quantitative comparability of the filtration ability of different-type masks is difficult to perform due to the variability of test methods and the broad range of materials tested in these studies. In addition, only the filtrations physics of particles somehow do not address the mitigation of potential exposure to the infective virus, possibly generating an under-appreciated potential infection risk for the susceptible individuals when masks are used.

During the COVID-19 pandemic, some scholars began to focus on the masks' filtration on respiratory viruses. Benjamin et al. (Leung et al., 2020) found that surgical facemasks can significantly reduce detection of influenza virus RNA in respiratory droplets (4%) and coronavirus RNA in both droplets (30%) and aerosols (40%), with a trend toward reduced detection of coronavirus RNA in respiratory droplets. Kawaoka et al. (Ueki et al., 2020) developed an airborne transmission simulator of infectious droplets laden with SARS-CoV-2 in a BSL3 facility, and showed that masks could mitigate both the dispersion and inhalation of SARS-CoV-2 in the air, while the virus could be detected regardless of the type of mask, even completely sealed when the virus emission concentration is extremely high. Cheng et al. (2021) proposed that the variations in mask efficacy can be explained by different regimes of virus abundance and are related to population-average infection probability and reproduction number. These findings provide further evidence on the protective effects of facemasks on the transmission of the real-world infective virus. Although manifold studies, what level the infection risk can be reduced to by wearing facemasks and how to explain the critical factors affecting their performance during the COVID-19 transmission process are aspects hardly known. There is still a lack of complete understanding of whether mandating public or community use of facemasks is promising to control or mitigate the transmission risk within a relatively acceptable level.

The study here confronts this problem by proposing a theoretical framework for a comparative evaluation on facemasks root in the transmission mechanism of SARS-CoV-2 from source patient to susceptible people. The results here show the capability in reducing infection risk of two commonly-used facemasks in the pandemic, i.e., surgical mask and N95, to help the public better understand and support policy responses. The virus-laden atomized droplets/aerosols are emitted by infector's respiratory activities, transporting in the environment, and inhaled by susceptible people, and finally the infection occurs (Liu et al., 2019; Liu et al., 2021a; Liu et al., 2021b; Chen et al., 2022). In the virus transmission process, face masks can potentially provide two types of protections to the wearers: (i) protecting the localized population from an infected mask wearer by trapping the virus-laden particles to reduce outward transmission, i.e., outward protection; (ii) protecting the mask wearers from ambient virus-laden particles by filtering the inhaled air, i.e., inward protection. In earlier studies, Tang et al. (Tang and Settles, 2008; Tang et al., 2011; Tang et al., 2013; Tang et al., 2009) visualized the airflow generated by a coughing, unfiltered as well as when the source person wears an N95 or a surgical mask. Impressive visualizations rich in details of the flow structures have attracted extensive attentions, and highlighted the need for investigating air leaks aroused due to improper fit of the mask to user's face. The exhaled airflow is redirected through narrow gaps causing multiple leaking jets that could extend upwards, downwards, and backwards quiet significantly (Viola et al., 2021), which also affects the mask efficiency in reducing infection risk.

This study analyzes the uncertainty in the protection efficiency of facemasks against SARS-CoV-2 transmission risk using a simplified theoretical model. In particular, the main goal of this study is to explore the risk level that wearing masks can reduce to. There are numerous studies on modeling risk of disease transmission (Li et al., 2021; Miller et al., 2021; Gao et al., 2021), however, mostly focused on the emission of virus-laden particles by infector's respiratory activities and the particle dispersion in indoor environments. The infection risk was usually denoted by the concentration trace gas or aerosols, neglecting the key transmission stages of virus from the environment to the exposed person: virus dynamics on exhaled particles, inhalation, and deposition in respiratory systems of the exposed person. Here we provide a comprehensive theoretical framework to assess SARS-CoV-2 transmission risk via expiratory aerosols. The framework considers the probable emission of SARS-CoV-2 from an infected patient, the generation of virus-containing aerosols, the subsequent transport and transformation through dynamic mechanisms in ventilated indoor spaces, the inhalation activities and deposition in the human respiratory system, and the infection rate of the virus. Both the inward and outward protection of surgical mask and N95 are considered in the model: masks worn by an infected subject can reduce the emission of SARS-CoV-2 into the ambient air (i.e., reduce the net exposure to the virus). In contrast, the mask worn by an exposed subject can reduce the inhalation of virus. *FE* and the faceseal leakage due to unfitting to face of the facemasks is fitted as a function of particle diameter using the published data. The virus loss in the environment due to ventilation, deposition, biological decay, and filtration are all considered. The infection risk is associated with the uncertainty of the above variables with a sensitivity analysis (SA). Conducting the uncertainty analysis on the facemask efficacy in reducing infectious risk and digging the key factors during the transmission process are expected to help people determine whether additional equipment is needed to protect themselves from infected patients.

2. Materials and methods

The evaluations of the facemask efficiency in reducing the infection risk need to take account of the various uncertainties of the factors during the transmission and infection process, as shown in Fig. 1. SA of the prediction model allows quantifying the variability in the infection risk of SARS-CoV-2 due to the simultaneous variations of the inputs.

2.1. Sample and data

During the disease transmission process from the virus emission by a source patient to the infection of a susceptible subject, the major input parameters considered in the sensitivity analysis include: (i) diameter d_i and number n_i distributions of the virus-laden droplets emitted during three respiratory activities; (ii) viral load of SARS-CoV-2, C_{RNA}, (iii) viral

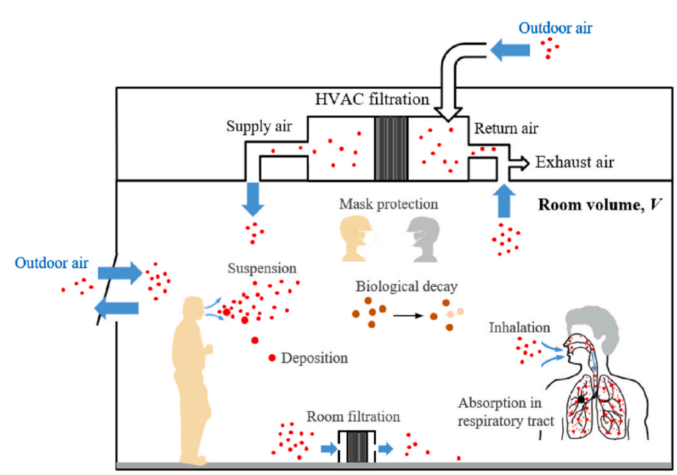

Fig. 1. Dilution and transmission of the exhaled virus in an indoor space.

conversion factor (or infectivity factor), φ_{in}, (iv) removal rate, λ, (v) breathing rate, q_{ex}, (vi) exposure time, t_d and (vii) *FE* of different facemasks, *FE*. Assumed the input parameters are independent of each other, Latin-hypercube samples (LHS) are generated to improve the stratification of samples over the probability space. To improve sampling efficiency and monitor sampling convergence, the infection risk statistics for two retrospective events on airborne transmission of SARS-CoV-2 are firstly conducted with different LHS numbers of 90, 900, 9000, and 18,000, respectively (as detailed in Section 3.1). Finally, a total of 9000 LHS of the inputs are generated under each scenario and the parameter variability are propagated through Monte Carlo simulations of the model in indoor environments.

2.2. Measures of variables

Assessing the probability of infection requires input of many variates that are either deterministically specified or described by continuous probability distributions functions (PDFs). The measures for the variables are:

- The diameter d_i and number n_i distributions of the virus-laden droplets emitted during three respiratory activities, i.e., speaking (asymptomatic infector), coughing and sneezing (symptomatic infector). The data in previous studies are extensively reported (Duguid, 1946; Chao et al., 2009; Morawska et al., 2009; Johnson et al., 2011; Zhu et al., 2006), as some shown in Table S2. In this work, d_i and n_i from Duguid (1946) were used because the distribution covers a wide range of droplet sizes, which is also in line with that reported by other more recent studies using modern aerosol characterization equipment (Chao et al., 2009) and is still widely adopted today in dynamics of airborne viruses or transmission model. During the outbreak of COVID-19, SARS-CoV-2 aerosols in air samples of Wuhan hospital areas were mainly found in two size ranges: 0.25–1 μm and >2.5 μm (Liu et al., 2020). Assuming the final droplet nuclei size after evaporation is approximately 32.5% of their initial diameter (Liu et al., 2017), the droplets with an initial diameter of <16 μm are considered here, with aerosols of <5.2 μm left after quick evaporation (within approx. 0.05s (Liu et al., 2021a)). Approximately, V_{ex} ~0.4 L of air is assumed to be exhaled during once coughing and sneezing with a short time period of T~500 ms. An air volume of 1/3 × 0.4 L is exhaled during speaking over the same time period (Chao et al., 2009). It is also assumed that the emission rate of droplets is constant during this time period of emissions.
- The viral load of SARS-CoV-2 in the exhaled droplets, C_{RNA}. The available data show a high variability in the concentration of RNA in respiratory secretions ranging from 7×10^6 to 1×10^{11} RNA copies/mL (Biguenet et al., 2021; Pan et al., 2020; Kim et al., 2020; To et al., 2020). In this work, we considered a normal distribution for the C_{RNA} during the incubation period of the index patient with the range of 10^6-10^{11} RNA copies/mL to cover the viral load during different phases of the illness as much as possible.
- The conversion factor (or infectivity factor) of the ratio between one infectious quantum and the infectious dose, φ_{in}. There is currently no more information available on the quantum generation data of SARS-CoV-2, so φ_{in} is barely used to represent the probability of a pathogen surviving inside the host to initiate the infection. Buonanno et al. (2020) extrapolated the orders of magnitude of φ_{in} with a variation range of 0.01–0.1. In this work, φ_{in} is regarded as one of the main uncertain inputs for the risk prediction model with a normal distribution, with the average and standard deviation of 0.025 and 0.125, respectively.
- The removal rate due to ventilation λ_v, deposition onto surface λ_d, biological decay λ_b, and filtration λ_f. λ_v are normally given by standards and guidelines according to the function of the space, and this study here takes samples of λ_v from a uniform distribution with a wide range of 0.5–30 h^{-1}. λ_v is considered a uniform distribution of 0.3–1.5 h^{-1}, λ_b approximately represented by a normal distribution with a mean of $1.75 \times 10^{-4} s^{-1}$ and a standard deviation of 0.43 s^{-1}, and λ_f has a value between 0 and 1 with a uniform distribution.
- The breathing rate of the exposed subject, q_{ex}. Values of q_{ex} are given by Adams et al. (Adams) with a uniform distribution of 0.49–1.38 m^3/h by considering different respiratory activity levels indoors, including resting, standing, light or moderate exercise.
- The exposure time of subjects exposed, t_d. Values of t_d in indoor environments is also an uncertain parameter, uniformly distributed from 5 min to 1 h in this study.
- The filtration efficacy of different facemasks, *FE*. In this study, *FE* of surgical mask and N95 measured by Grinshpun et al. (2009) is used because in their work the contributions of two penetration pathways through masks for particles are clearly differentiated, i.e., through the face seal leakage and filter medium, as the data shown in Figure S1. In the following model procedure, *FE* of surgical mask and N95 is fitted as a function of particle diameter to a logarithmic bi-Gaussian distribution (i.e., a logarithmically transformed bi-Gaussian distribution) as follows:

$$FE = 1 - FE_{max} \times exp\left(\frac{-(log_{10}d - log_{10}d_{ae})^2}{2(log_{10}\sigma)^2}\right) \tag{1}$$

2.3. Models and data analysis procedure

To evaluate the airborne transmission risk of SARS-CoV-2 induced by a symptomatic or asymptomatic infected individual in indoor space, four key stages in the transmission and infection process should be obtained in the prediction model: (i) the virus emission from an infected subject; (ii) the exposure to virus concentration in a ventilated space; (iii) the virus received by an exposed susceptible subject; and (iv) estimation of the probability of infection based on Wells-Riley model.

Firstly, the virus is emitted into the surrounding along with the droplets generated by respiratory activities of the infected subject. The evaluation of SARS-CoV-2 generation rate during expiratory activities of an infected subject in the room is expressed as:

$$\dot{E}_{RNA,i} = \varphi_{in} C_{RNA} V_{ex} / T C_{drop,i} V_{drop,i} \cdot 0.325^3 \tag{2}$$

in which $\dot{E}_{RNA,i}$ (quanta/s) is the emission rate of SARS-CoV-2 RNA copies carried by *i*th mode droplet, $C_{drop,i}$ is the number concentration of in exhaled air, $V_{drop,i}$ (m^3) is droplet volume determined by the droplet diameter d_i and number n_i, C_{RNA} (RNA copies/mL) is the viral load of SARS-CoV-2 in the exhaled droplets and V_{ex} is the exhaled air volume (m^3). The pathogens themselves are assumed to be nonvolatile, unaffected by the evaporation of exhaled droplets. φ_{in} is the conversion factor (or infectivity factor) of the ratio between one infectious quantum and the infectious dose expressed in viral RNA copies.

Secondly, the virus-laden aerosols are transported and diluted in indoor air. A mass conservation model for the room is applied to quantify the virus transport by relating c_i (t) to $\dot{E}_{RNA,i}$:

$$\frac{dc_i}{dt} = \frac{\dot{E}_{RNA,i}}{V} - \lambda c_i \tag{3}$$

$$\lambda = \lambda_v + \lambda_d + \lambda_b + \lambda_f \tag{4}$$

Eq. (2) assumes that quanta are generated at a single point at a constant rate $\dot{E}_{RNA,i}$, and are then mixed rapidly in air in an air fully mixing space so that the rate of change in the quantum concentration in the space, c_i (t) (quanta/m^3), with time, t (s), is approximately the same regardless of the sampling point. In Eq. (2), the emitted quanta are diluted by several mechanisms that can be normalized by the volume of the room V (m^3), and combined into a total loss rate, λ (s^{-1}) (see Fig. 1). λ_v, λ_d, λ_b, λ_f are the loss rate (s^{-1}), induced by ventilation, deposition onto surfaces, biological decay, and filtration, respectively. Therefore, the time average concentration of RNA copies $c_{a,i}$ (quanta/m^3) for the duration of the event t_d (s) is

$$c_{a,i} = \frac{1}{t_d}\int_0^t c_i(t)dt \tag{5}$$

Thirdly, the virus-laden aerosols are inhaled by the exposed subjects with a breathing rate of q_{ex} (m^3/s). The deposition efficiency depends on the particle size and the region of the airway where deposition occurs (Hinds, 1999). A total deposition rate in the respiratory system is considered here and calculated using the model developed by the International Commission on Radiological Protection (Hinds, 1999), expressed as:

$$\eta = IF\left(0.0587 + \frac{0.911}{1 + exp(4.77 + 1.485 ln d_i)} + \frac{0.943}{1 + exp(0.508 - 2.58 ln d_i)}\right) \tag{6}$$

where d_i is particle diameter in unit of μm, and IF is inhalable fraction, defined as

$$IF = 1 - 0.5\left(1 - \frac{1}{1 + 0.00076 d_i^{2.8}}\right) \tag{7}$$

The total number of quanta deposited in the respiratory system of an exposed subject can be expressed as

$$\mu = \sum q_{ex} t_d c_{a,i} \eta \tag{8}$$

We use the Wells-Riley model to assess the infection risk, shown as:

$$p(\mu) = 1 - exp(\mu) \tag{9}$$

in which p is the probability of infection, μ is the quanta exposure.

Finally, the Sobol's variance-based SA (Sobol, 2001) is performed to quantitatively attribute the variance of p to the uncertainties or variabilities of the model inputs. Two sensitivity induces, i.e., the main effect S_i and the total effect S_{Ti} are used to conduct the discussion in this study. S_i is the proportion of output uncertainty removed by fixing a parameter X_i. S_{Ti} is the proportion of uncertainty associated with the variability of the parameter X_i and all its interactions with other parameters in the model, which can be interpreted as the expected output variance when only X_i is left undetermined (Saltelli et al., 2010) (more details are shown in **Supplementary Information**). MATLAB 2017a is used for the execution of sampling and computation of sensitivity induces.

The simulations of the probability of airborne transmission of SARS-CoV-2 were performed applying a Monte Carlo method under four scenarios:

- *Scenario A.* No masks are worn on both infected subject and exposed subject.
- *Scenario B.* Masks are worn by an infected subject (masks provide outward protection).
- *Scenario C.* Masks are worn by the exposed subject (masks provide inward protection).
- *Scenario D.* Masks are worn by both infected subject and exposed subject (masks provide outward protection and inward protection).

3. Results

3.1. A retrospective assessment of airborne transmission of SARS-CoV-2 with no facemasks

Two cases of airborne transmission of SARS-CoV-2 have been evidenced in a restaurant in Guangzhou, China (Li et al., 2021; Lu et al., 2020) and at a choir practice in Skagit, USA (Miller et al., 2021; Hamner et al., 2020). In the two events, no face masks were worn by involvers. Based on the available information documented in references, here a retrospective infection risk assessment is first simulated using our proposed model. ***Case 1***: According to the available documents, the restaurant can be divided into different airflow zones with well-mixed conditions, due to the installation and use of the fan coils. We focus only on the zone involving table A at which the index patient sat and tables B and C at which the other five infected people sat, which covers a zone volume of approximately 45 m^3. The average exposure time of people sitting at tables B and C is roughly 66.7 min. The tracer gas decay experiments reported a low air exchange rate (mostly due to the absence of an outdoor air supply) in the range of 0.56–0.77 h^{-1}. ***Case 2***: The choir practice composed of 61 choir members lasted 2.5 h, at which one person was known to be symptomatic, 32 confirmed and 20 probable secondary COVID-19 cases occurred. The air exchange rate is reported to be roughly 0.5 h^{-1}. Detailed information for two case simulations is listed in Table 1.

The number of 90, 900, 9000, and 18,000 LHS is sampled, and the simulated results in the restaurant and at the choir rehearsal shown in Fig. 2 and Figure S2, respectively. The results of Samplings 3 and almost overlap with each other. Thus, simulations run with 9000 LHS in the following uncertainty analysis. In Eq. (9), the probability of infection p can also be expressed as the ratio of the expected number of infection cases C to the number of exposed susceptible S. In the restaurant, the documented probability of infection (i.e., attack rate) is 45.5%, i.e., 5 out of 11 people sitting at tables B and C (members sitting at table A were excluded as they could easily have been infected through other infection routes like close contact route), almost consistent with the mean value of 46.5% in our simulations (in Fig. 2 with Sampling 3). While at the choir rehearsal the reported secondary attack rate is 53.3% among confirmed cases and 86.7% among all cases, different from the simulated mean value of 68.2% (in Figure S2 with Sampling 3). Different from normal speaking of exposed subjects in the restaurant, the droplet emission during loudly singing in the choir rehearsal is positively correlated with the amplitude of vocalization (Asadi et al., 2019), however, limited data on droplet distributions generated by singing is available from published articles. Though the infected subject is reported to be symptomatic, that we use the droplet distributions by a coughing during the rehearsal practice still causes the probability of infection overestimated to some extent.

Table 1
Detailed information for the retrospective risk assessment in a restaurant and at a choir rehearsal.

Inputs	Distributions	
	Restaurant in Guangzhou, China	Choir rehearsal in Skagit, USA
Zone volume, V (m^3)	Constant, 45	Constant, 810
Viral load, C_{RNA} (copies/mL)	N (3.75×10^{17}, 3.75×10^{16})	
Removal rate due to ventilation, λ_v (/s)	U (1.56×10^{-4}, 2.14×10^{-4})	Constant, 1.39×10^{-4}
Removal rate due to deposition onto surface, λ_d (/s)	U (8.3×10^{-5}, 4.2×10^{-4})	
Removal rate due to biological decay, λ_b (/s)	N (1.75×10^{-4}, 0.43)	
Removal rate due to filtration, λ_f (/s)	U (0, 1)	
Volumetric breathing rate, q_{ex} (m^3/h)	Constant, 1.38	Constant, 1.38
Exposure time, t_d (s)	Constant, 3600	Constant, 9000
Conversion factor, φ_{in}	N (0.025, 0.125)	

Note: N refers to normal distribution with a mean value and a standard deviation in parentheses, and U refers to uniform distribution with maximal and minimal values in parentheses.

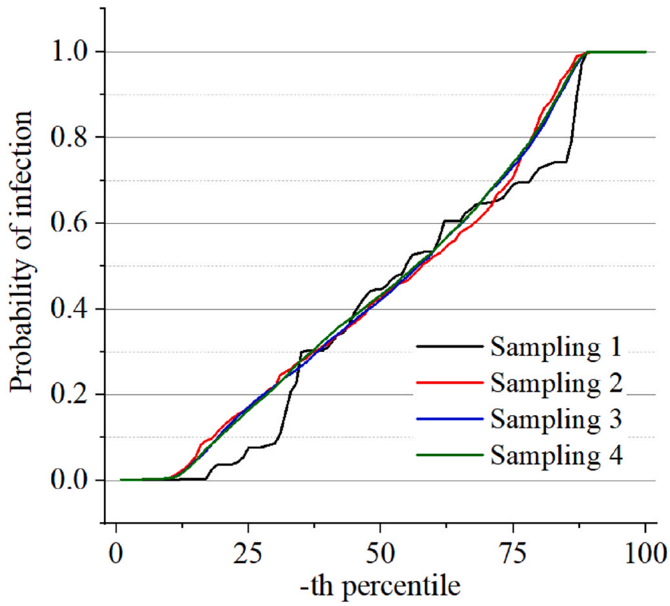

Fig. 2. Comparison of different numbers of LHS in calculating the probability of infection in the restaurant in Guangzhou, China.

3.2. *Relative contributions of variables to the uncertainty of SARS-CoV-2 infection risk*

In the following analysis, we evaluate the impacts of input variables of the model to the uncertainty of the transmission probability of SARS-CoV-2 in typical public indoor environments, such as public classrooms, restaurants, and waiting rooms/halls at railway stations and hospitals, etc. In the following Monte Carlo simulations, the volume is set as 300 m^3. PDFs of variables are demonstrated in Section 2.2. Fig. 3 gives the comparisons of the emission rate of SARS-CoV-2 and the final infection risk caused by three different respiratory activities of an infected patient. It reveals that the infection risk induced by a normal speaking patient is $\sim 10^{-3}$. People with symptoms (who should in any case be self-isolating) tend to have a high viral load and more frequent violent respiratory exhalations. The high emission rate produces considerable c_i in surrounding air, thus increasing the individual risk. It should be noted that a realistic exhalation activity, especially coughing and sneezing are transient processes, a constant emission rate here that equals the instantaneous release during the duration of the event may overstate the transmission probability.

Relative importance of viral load, removal rate (including loss rate induced by ventilation, deposition onto surfaces, biological decay, and filtration) to the uncertainty of the simulated output is denoted by S_i in Sobol's analysis (see Figure S3), and the normalized contributions are shown in Fig. 4 for comparisons. It shows that there is a difference in relative susceptibilities to the infection risk when the transmission is caused by different respiratory activities. The infectivity factor φ_{in} denoting the conversion relationship between one infectious quantum and the infectious dose expressed in viral RNA copies is the most important source of variance in transmission probability of SARS-CoV-2 regardless of the emission rate. However, the exact value of φ_{in} is currently hard to determine in risk assessment due to limited information available on the quantum generation data of SARS-CoV-2. Second to φ_{in} is the viral load, whose main effects ranged mostly ranged within 11%–36%, 33%–43%, and 43%–72% when virus-laden aerosols are emitted by speaking, coughing, and sneezing, respectively. Considerable viral loads have been detected in the nasal and throat swabs of asymptomatic and minimally symptomatic patients (Zou et al., 2020), which suggests a high transmission potential in public places. Further, it implies that a high number of infected people without the presence of a superspreader in the environment (i.e., an infected person with the highest viral load), but rather a co-existence of emission conditions can also lead to a highly transmission event. In addition, the uncertainty of exposure time of the susceptible person in indoor space accounted for approx. 3%–20% of the variance of final infection risk. The importance of the removal rate is also significant in the Sobol's analysis but determined by the respiratory activities. In detail, as shown in Fig. 4, the loss rate induced by deposition onto surfaces can be ignored, which is reasonable in the airborne transmission assumption. The loss rate

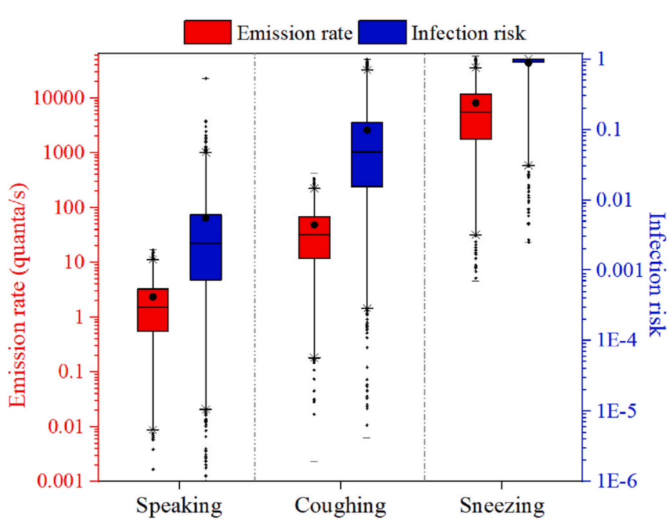

Fig. 3. Virus emission rate generated by three-type expiratory activities and probability of infection.

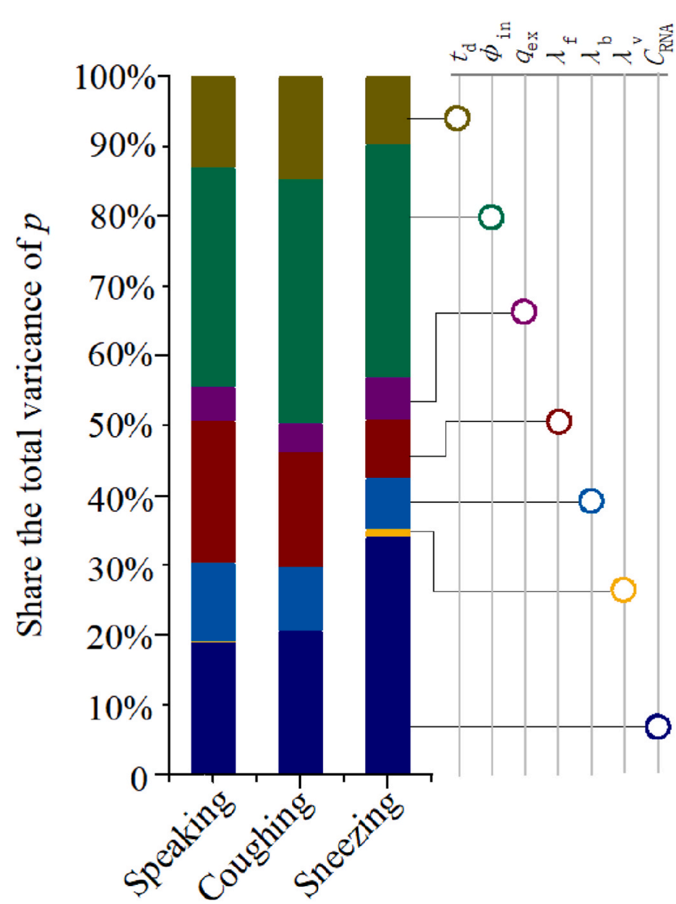

Fig. 4. Normalized contributions of all parameters to the variance of *p*.

induced by filtration λ_f and ventilation λ_v under sneezing condition seems to play important parts in the present simulations.

3.3. Inward protection efficiency of face masks with mask on the susceptible subject

Uncertainty of the protection efficiency of surgical mask and N95 are tested with the faceseal leakage considered. The protection efficiency of masks is discussed by the percent decrease in the simulated infection risk of COVID-19. Fig. 5 show the box plot of the emission rate of quanta generated by speaking and the infection risk with the face mask worn by a receiver, with the percentiles shown in Figure S4. Inward protection efficiency of mask is used to quantify the protect capability of the mask worn by the exposed subjects by filtering out virus-laden aerosols moving in the inward direction through the mask, from the ambient air to the wearer's respiratory tract. Therefore, it can be seen from Fig. 5 that there is no obvious difference of the emission rate when the face mask provides inward protection, while the infection risk has a significant decrease due to the reduction of inhaled virus. The inward protection efficiency is found to be N95 > Surg.-fit > N95-leak > Surg.-leak, with the 50th-percentile of the infection risk in Figure S4 of 7.5 $\times$ 10^{-6}, 4.9 $\times$ 10^{-5}, 9.9 $\times$ 10^{-5} and 1.7 $\times$ 10^{-4}, respectively, significantly lower than the risk of 2.3 $\times$ 10^{-3} with no masks. Obviously, the protection levels determined for N95 were slightly higher as compared with those obtained for the surgical mask when masks are assumed to fit well with face, and a maximum reduction of three orders of magnitude can be achieved when masks provide inward protection. The percent decrease of infection risk is 99%, 97%, 95% and 92%, respectively. A significant difference in protection efficiency with faceseal leakage also shows that facial fit is an important factor in evaluating different types of masks. The difference is approximately an order of magnitude on infection risk reduction of the protective effect of the same type of mask. It suggests that the leakages between the mask and human face plays an important role in the airflow pattern, and more virus-laden aerosols may disperse into the surrounding air through the faceseal, as shown in visualizations and numerical simulations (Viola et al., 2021; Chen et al., 2014). The priority in mask/respirator development should be shifted from improving the *FE* of the medium to establishing a better fit that would eliminate or minimize faceseal leakage.

Figures S5 and S6 present similar trends of mask protection (i.e., N95 > Surg.-fit > N95-leak > Surg.-leak) with high intensity exhalation behaviors, i.e., coughing and sneezing. The 50th-percentile of the infection risk in Figure S5(b) is 1.7 $\times$ 10^{-4}, 2.0 $\times$ 10^{-3}, 9.5 $\times$ 10^{-5} and 3.3 $\times$ 10^{-3}, respectively, generally reducing the risk at least in an order

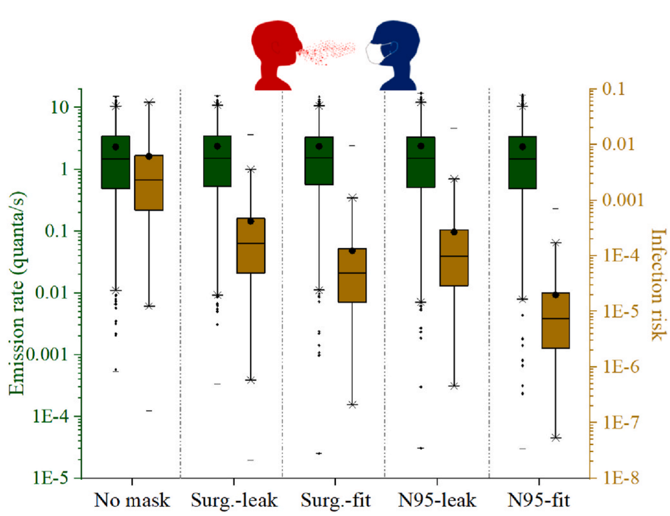

Fig. 5. Box plot of infection risk induced by speaking with masks one the susceptible subject.

of one compared with 0.05 of no masks, despite higher risk levels. The exposed subjects are infected with a higher possibility by the virus-laden aerosols emitted by sneezing, as seen in Figure S6, also response to the above finding that viral load contributes largely to the infection risk. Surgical mask and N95 can effectively reduce the risk (the 50th-percentile) to approximately 0.14 and 0.02 respectively, with the protection efficiency of 85% and 97% when the mask fits face well; in contrast, the percent decrease is only 56% and 69% with the faceseal leakage of face masks considered. The results imply that surgical masks are effective at reducing virus transmission risk in public space, even induced by an infected subject with obvious symptoms, although the protection efficiency is not as good as the situation with asymptomatic infector.

3.4. Outward protection efficiency of face mask with mask on the infected subject

The outward protection efficiency of masks is used to quantify the protection capability of a mask for source control, to filter out virus-laden aerosols moving in the outward direction through the mask, from the wearer to the ambient air. Results of simulated infection risk transmitted via aerosols by speaking is shown in Figure S7. There are large variations in the emission rate of SARS-COV-2 for different masks and fittings to the face due to the reduction in emitted aerosols into the surrounding air. The infection risk of the exposed subjects under different simulated cases shows similar trends with the emission rate. The protection efficiency of different-type face masks still ranks similarly while providing outward protection, i.e., N95 > Surg.-fit > N95-leak > Surg.-leak. In details, the infection risk can be reduced to 7.6 $\times$ 10^{-6}, 4.9 $\times$ 10^{-5}, 1.0 $\times$ 10^{-4} and 1.6 $\times$ 10^{-4} with the percent decrease of 99%, 97%, 95% and 93%, respectively, nearly the same with the inward protection efficiency. That mean, the transmission risk can also be largely reduced by three orders of magnitude by N95 and two orders of magnitude by surgical mask when masks fit the infector's face well. Results of infection risk induced by aerosols generated from coughing and sneezing can be found in Supplementary Information. In a coughing condition (see Figure S8), the infection risk of indoor exposed subjects can be reduced to 1.7 $\times$ 10^{-4}, 9.5 $\times$ 10^{-4}, 2.0 $\times$ 10^{-3} and 3.4 $\times$ 10^{-3}, significantly lower than the risk of 0.05 when the source patient does not wear masks. Under this condition, the outward protection efficiency of N95, Surg.-fit, N95-leak and Surg.-leak are respectively 99%, 97%, 95% and 93%. In contrast, when the virus-laden aerosols are emitted by sneezing (see Figure S9), the outward protection is only 97%, 84%, 69% and 55%. The statistical data of the uncertain results suggests that for the same-type mask, the difference of inward and outward protection efficiency of masks in reducing the airborne transmission probability is not significance. Wearing facemask can reduce the uncertainty of infection risk induced by different respiratory behaviors, while the protection efficiency of different-type masks is differed by the respiratory activities.

The simulated infection risk with masks worn on both infector and receiver under three respiratory activities are shown in Figure S10–S12. Both surgical mask and N95 show the best performance when provide protection in both directions. There is a synergistic effect when both the virus receiver and virus emitter wear masks (surgical mask or N95) to prevent the transmission of infective aerosols. It can be found that the 50th percentile of the infection risk of the receiver is greatly decreased to a low level of 10^{-5}–10^{-8}, even the face leakage of mask is considered.

Table 2 presents a guide to how transmission risk level may vary with mask types and whether face masks are worn by infected subject or/and the exposed subject, with the 50th-percentile of the simulated results with 9000 LHS of each blank in the table. These estimates apply when the infected person is asymptomatic and virus-laden aerosols are generated from normal speaking. It turns out that it is desirable for individuals to wear masks in public spaces in terms of an acceptable infection risk level ($< 10^{-3}$). When masks are worn on both the infected and exposed subjects, the transmission probability of SARS-CoV-2 can

Table 2
Risk of SARS-CoV-2 transmission (50th percentile of simulated results with 9000 LHS of each blank) from asymptomatic people while speaking with different-type mask protections.

Low — High

		Mask on receiver				
		No mask	Surg.-leak	Surg.-fit	N95-leak	N95-fit
Mask on source	No mask	2.3e-3	1.7e-4	4.9e-5	1.0e-4	7.5e-6
	Surg.-leak	1.6e-4	1.1e-5	3.4e-6	7.4e-6	2.4e-7
	Surg.-fit	4.9e-5	3.4e-6	9.7e-7	2.1e-6	1.7e-7
	N95-leak	1.0e-4	7.0e-6	2.1e-6	4.3e-6	3.5e-7
	N95-fit	7.6e-6	5.2e-7	1.6e-7	3.3e-7	2.6e-8

Inward protection

Outward and inward protection

Outward protection

be reduced by more than two orders of magnitude even with faceseal leakage considered. Li et al. (2020) claimed that 79% of the actual infected cases were infected by individuals with "mild, limited, or no symptoms". That means, aerosols generated from normal speaking are increasingly considered to be a likely mode of disease transmission. Our results highlight the practical importance of wearing mask in reducing the personal infection risk, especially in public places where more asymptomatic infected individuals may be found.

4. Discussion

The study is based on an uncertainty analysis of the protection efficiency of surgical mask and N95 to response the strategies to cope with COVID-19 pandemic. The proposed theoretical framework, in particular, considers the transmission process of SARS-CoV-2 from virus emission by the source patient to the infection of the susceptible person.

The findings of the work here reveal that the infectivity factor is the most important source of variance in infection risk. However, the exact value of φ_{in} for novel viruses is hard to determine in risk assessment, especially in the early stage of a pandemic. Virus removal rate by the environment is another key factor, especially in crowded spaces with high transmission probability. In the recent report by Li et al. (2021), a measured ventilation rate of 0.9 L/s per person may deteriorate the COVID-19 outbreak in a restaurant in Guangzhou, China, where the transmission probability is up to 45.5% (excluding the members seated at the same table with source as they could easily have been infected through other infection routes like close contact route). Different findings were reported by Buonanno et al. (2020) that the ventilation rate does not lead to a significant reduction in risk in an environment if the infection risk can be accepted (i.e., 10^{-4} or 10^{-5}). Together with the influence of viral dynamics, ventilation is advocated to dilute virus concentration, and can also change an environment from virus-rich to virus-limited conditions, as Cheng et al. (2021) suggested, which may be particularly important for medical centers with relatively high SARS-CoV-2 abundances.

Our analysis gives contrasting results of the protection efficiency of different masks in terms of the infection risk of wearers, instead of a single filtration capability in blocking particles. We find that in indoor environments under conditions of low virus emission rate, like asymptomatic infected individuals, surgical mask is widely advocated to mitigate transmission to a low risk level. More-advanced masks like N95 and other protective equipment are more required in indoor environments with potentially high virus emissions, including medical centers and hospitals. For the same type of mask, no significant difference is found here between outward protection efficiency and inward protection efficiency. Similar observation was reported in the work of Pan et al. (2021), in which they measured the inward and outward protection efficiency of 11 face coverings, and revealed that the outward protection efficiency tended to be higher than inward protection efficiency, while the difference was not significant in most experimental cases. However, it should be noted that in our quantitative model the exhaled viruses are assumed to be mixed uniformly by air in the environment after a long time, which means that short-range airborne transmission and droplet transmission are not considered here. In recent airborne transmission simulation experiments of SARS-CoV-2 (Ueki et al., 2020), the outward protective efficiency of the surgical mask and N95 was obviously higher when the virus spreader wore masks. Different from the current model, in their test chamber with limited space, both droplet and short-range airborne transmission were likely to dominate the transmission of SARS-CoV-2; however, in a short distance range large-size infectious droplets or aerosols can be blocked largely, which was the main effect that produced obvious discrepancies between inward and outward protection efficiency. Considering the multi-routes of SARS-CoV-2 transmission (Tang et al., 2021), a synergistic effect of combining face masks with other preventive measures is advocated to reduce the virus transmission, such as social distancing and self-isolation. For example, in the large prospective U.S. cohort study of 198,077 participants conducted by Kwon et al. (2021), it was found that the individuals in communities with the greatest social distancing had a 31% lower risk of COVID-19, and a 62% reduced risk with the synergistic effect with the use of face masks.

This study has provided supports for the efficacy of mask-wearing in mitigate the COVID-19 transmission in view of non-pharmaceutical interventions in public spaces. The growing numbers of COVID-19 related infected individuals and deaths worldwide have facilitated the development of different types of vaccines based on viral vector, protein subunit and nucleic acid-RNA (de Vlas and Coffeng, 2021; Abbasi, 2020). COVID-19 vaccines have shown >90% effectiveness in preventing SARS-CoV-2 infection, and an estimation of 66% even with B.1.617.2 (Delta) predominant (Coccia, 2022; Baden et al., 2021; Fowlkes et al., 2021). In the recent report, Naleway et al. (2022) associated the COVID-19 infection risk with both the vaccinations and the use of face masks. Their data showed that less use of facemask was associated with a higher infection risk for unvaccinated participants during exposure to persons who may have COVID-19. Face masks use can add the protective benefit of among both unvaccinated and vaccinated people despite Delta variant predominance.

5. Conclusions

In the context of rapid spread of COVID-19 globally, there is a lack of consensus on wearing facemasks in preventing SASR-CoV-2 transmission amide the pandemic. Uncertainty of the protection efficiency of surgical mask and N95 in reducing SASR-CoV-2 infection risk was challenged with a sensitivity analysis. This study suggests that there is a difference in relative susceptibilities of variables to the infection risk during the pandemic, such as virus dynamics, environment factors and individual exposures, especially when the transmission is caused by patients with different symptoms. The use of facemasks can effectively reduce the uncertainty of infection risk to a lower level ($< 10^{-3}$) with all variables considered in the SASR-CoV-2 transmission model. A synergistic implementation of wearing face masks with other preventive measures is advocated to mitigate the SARS-CoV-2 transmission.

However, there are limitations in this work. The mass conservation model for the dispersion of virus indoors assumes that the virus is mixed uniformly in the space. Both proximity and confinement effects are ignored, which may cause a bias while evaluating the protection efficiency of facemasks. Further, both coughing and sneezing of the infected subject are simplified as continuous emission source in the predictions, which makes the infection risk of the exposed subject larger than that in the real situations. There are more challenges to such studies of factors determining the transmission of SARS-CoV-2 and there is need for much more insights into the complex relations among the infection risk, environmental factors, social policies, etc., to cope with and/or prevent pandemic threats like COVID-19.

Author statement

No conflict of interest exits in the submission of this manuscript, and manuscript is approved by all authors for publication. I would like to declare on behalf of my co-authors that the work described is original research that has not been published previously, and not under consideration for publication elsewhere, in whole or in part. All the authors listed have approved the manuscript that is enclosed.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2022.119167.

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